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Beach Erosion at Waimea Bay, Oahu, Hawaii[1]

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ABSTRACT: Waimea Beach on the island of Oahu, Hawaii, is a popular recreation area, which is presently endangered by severe erosion. The extent of shoreline erosion has been determined from comparison of an 1884 survey map with aerial photographs from the period 1928–1975, and from measurements of the changes in the vegetation line during that time. The Waimea section of Oahu's shoreline has receded about 200 ft in this 47-yr period. This erosion is caused primarily by storms that move the beach sand into deeper waters from which it cannot return to the beach and the lack of supply of new sand to the beach. Sand mining and abrasion also have contributed to the retreat of the shoreline.

Continued periodic measurements and aerial surveys would be valuable in tracking the regression of the shoreline and useful for planning the future of public facilities located in Waimea Bay.

PROBLEMS RELATED TO EROSION of a coastline are often first noticed when people see that man-made structures are in danger of being washed into the sea. In areas where there are no man-made structures along the shore, coastal erosion problems usually are not recognized. One such area is the beach in scenic Waimea Bay on the north shore of Oahu, Hawaii (Figure 1), where the shoreline has eroded almost 200 ft in the last 47 yr, with little apparent public concern for the problem.

Our present understanding of coastal processes in Hawaii and an analysis of the history of the coastal retreat at Waimea, together with information on past sea level stands and the geomorphology of the Waimea area, allow us to deduce the causes of this erosion. We therefore predict what is likely to happen in the future.

Waimea Bay is an embayment at the mouth of a valley formed by subaerial erosion of the Koolau volcano by Waimea River (Figure 2). This valley, now filled with alluvium because of changes in sea level relative to the island, was once graded to a depth of 215 ft below present sea level (Coulbourn, Campbell, and Moberly 1974) and possibly deeper.

Other than the valley, the most prominent topographic feature in the area is the sea cliff that truncates the northwest end of the Koolau range and is a continuous feature except where incised by alluviated valleys such as Waimea. Along most of this coast, the base of this cliff is fronted by a narrow strip of recent alluvium and a calcareous sand beach. In the immediate vicinity of Waimea Bay, this is not the case; the headlands enclosing the bay are remnants of the basaltic valley walls that now extend seaward of the general cliff line at least to the present shoreline and possibly beyond.

Offshore of these rocky headlands, water depth increases rapidly to 33 ft and then grades more gently to a cliff formed by the −60-ft stand of the sea called Makai Range (Stearns 1974). Off Waimea Bay itself, a large sand-bottomed channel has been traced to depths of at least 215 ft (Figure 3). Coulbourn et al. (1974) found this channel to be a Pleistocene stream channel that was cut to the Kahipa-Mamala −350-ft sea level stands (Stearns 1978). Stearns (1978) believes

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FIGURE 1. Aerial view of Waimea Bay, Oahu, November 1980.

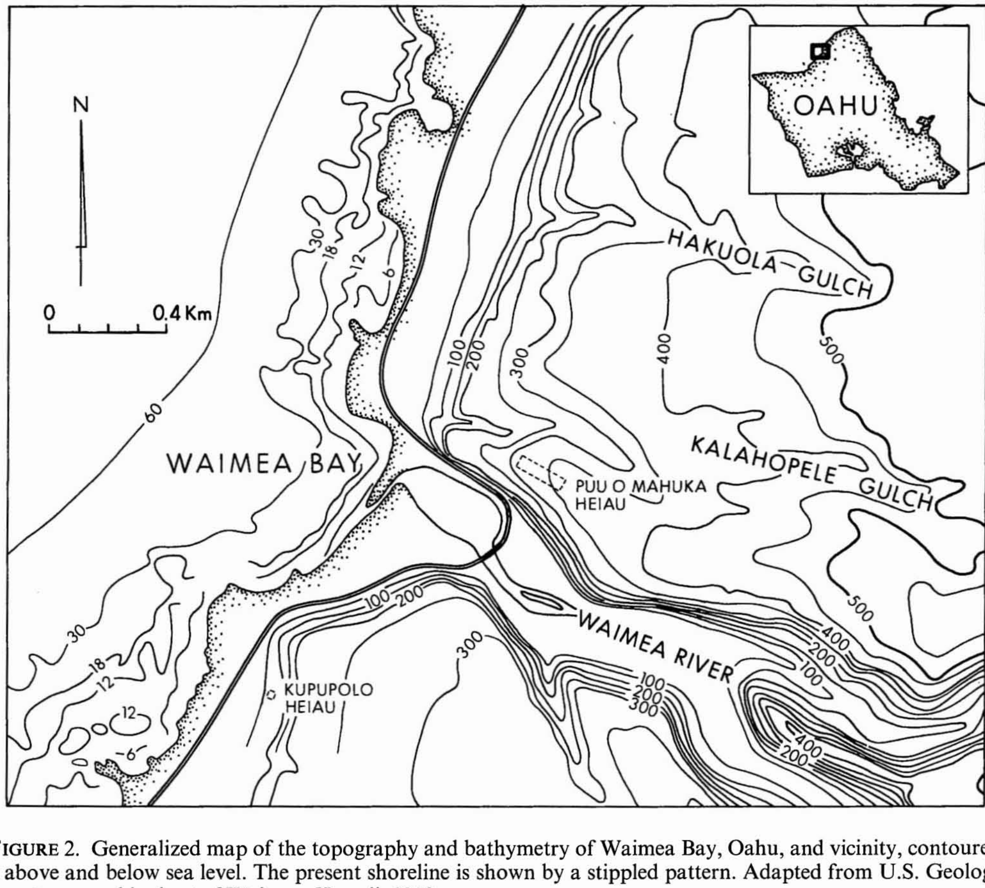

FIGURE 2. Generalized map of the topography and bathymetry of Waimea Bay, Oahu, and vicinity, contoured in feet above and below sea level. The present shoreline is shown by a stippled pattern. Adapted from U.S. Geological Survey topographic sheet of Waimea, Hawaii, 1952.

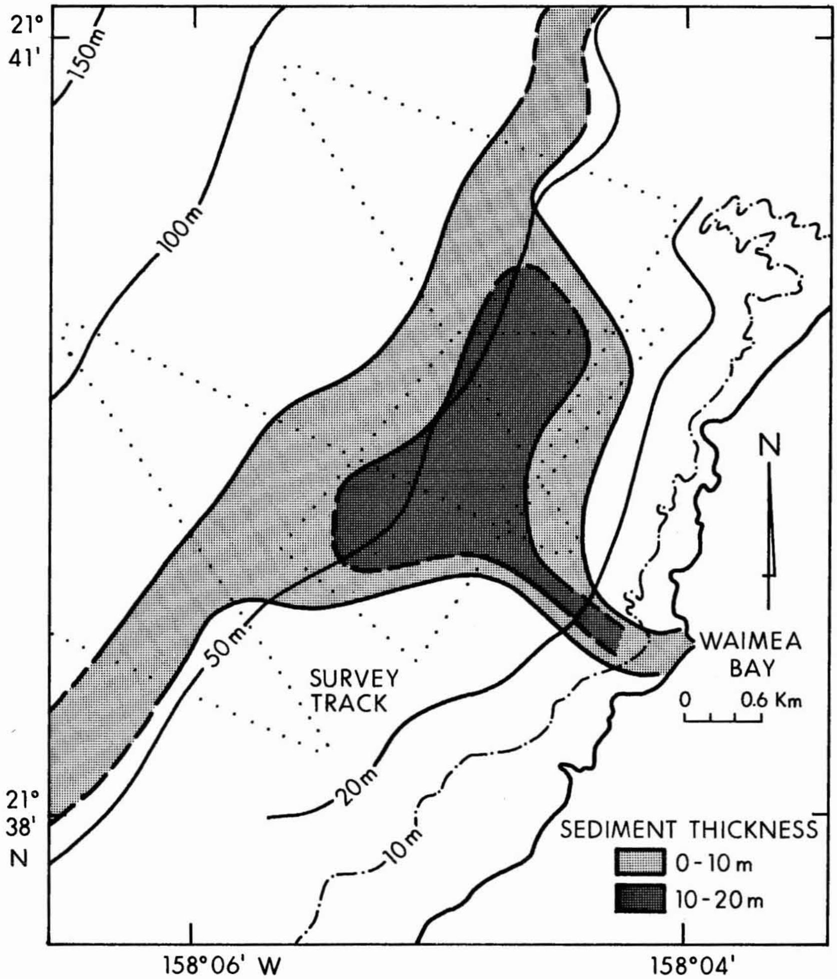

FIGURE 3. Sediment thickness offshore of Waimea Bay, Oahu, shows a continuous sediment body along the −65-m contour. This indicates that there was a continuous beach along this coast when sea level was lower. Contour lines represent meters below sea level. Modified from Coulbourn et al. (1974). Bathymetric contours from Pararas-Carayannis (1965).

that these stands represent broad coastal areas that were exposed above sea level.

The concept of a littoral sand budget, where the rates of sand production, loss, and transport into and out of a segment of coast affect the magnitude and rate of change in beach volume, was first applied to Hawaii's beaches by Moberly and Chamberlain (1964). They showed that for a beach to be in equilibrium with the forces acting upon it (that is, to experience no permanent erosion or accretion), there must be a balance between the sediment added to and that lost from the beach system. At Waimea, the budget appears to be not in equilibrium. To understand this nonequilibrium situation, we review aspects of coastal processes in Hawaii.

Unlike most continental beaches composed primarily of sand delivered by stream runoff, most beaches in Hawaii are made of carbonate sand of marine origin. These carbonate sands are produced by organisms with calcareous tests or shells that live on the reefs and in the shallow water surrounding the islands. Moberly, Baver, and Morrison (1965) determined that this calcareous sand is composed of grains produced from fragments of foraminifera, mollusks, red algae, echinoids, and corals, in order of decreasing importance. Other natural sources of sand in Hawaii are basalt fragments and mineral grains that are eroded from the islands and sand-size material produced by erosion of fossil calcareous reefs and other sedimentary rocks exposed near present sea level.

Although the original source of most of the sand is biological, the sand actually being added to the beach at any given time may come from a number of areas where the sand has been in storage. Probably the most important such source is shallow-water deposits adjacent to the shoreline, either sand pockets on the fringing reef or channels of various sizes that cross the reef. Another source is sand added to the beach by the action of offshore winds, coastal erosion, or flooding of intermittent streams. Finally, sand may be brought in to construct beaches or as a shoreline protection measure. Studies of the importance of these different sources show that the largest potential contributions are from the shallow fringing reefs and sand channels offshore (Moberly and Chamberlain 1964).

Although offshore, sand-bottomed channels are the sources of large volumes of sand, they are also the principal routes for the transportation of sand to deep water (Moberly 1968). These channels, originally formed during Pleistocene low stands of the sea, form an integral part of the water–sediment circulation pattern. Studies on Kapaa reef, Kauai, show that water and sediment move across the fringing reef in small channels. The sand is then transported along the shoreline before it is moved offshore via larger channels (Inman, Gayman, and Cox 1963). The sand in the larger channels is not necessarily lost offshore, since changing wave conditions can return this sand to the beach. Once the sand gets below 50–65 ft in depth, however, it probably is lost from the beach system.

Major sand transport through the sand-bottomed channels is probably concentrated during storm events, tsunamis, or hurricanes. Large winter storms can carry sand offshore by rip currents, and this sand may be permanently lost if it is deposited at such great depths that summer waves cannot return it to the beach system.

On a geologic time scale, tsunamis occur frequently in Hawaii. Unfortunately, there have been few detailed studies of their effect on beaches. The damage caused by the 1946 tsunami varied greatly because of factors such as bathymetry and the orientation of the shoreline, but beach changes did not seem to be any greater than those produced by large winter waves (Shepard, Macdonald, and Cox 1950). It is conceivable, however, that tsunami runoff could permanently remove sand offshore through the large sand channels.

Although the Hawaiian Islands have not been hit by a hurricane since 1957, recent study shows that the tracks of ten tropical storms or hurricanes passed near Hawaii during the period 1950–1974 (Tamaye and Rocheleau, 1976). It has been predicted that 50-ft waves could be generated by a hurricane in Hawaiian waters. Although there is no record of coastal erosion due to hurricanes in Hawaii, it is assumed that they have the potential to cause as much erosion as the largest winter storm.

Other avenues of loss of sand from Hawaiian beaches detailed in Moberly (1968) include paralic sedimentation, abrasion, deposition landward of the beach on storm beaches and in dunes, and removal by humans. Some of these may result in only a temporary removal from the beach system; for example, sand deposited in fossil beach ridges or in dunes may be returned to the active beach system during periods of coastal retreat.

METHODOLOGY AND HISTORY OF EROSION IN WAIMEA

Our study of erosion at Waimea Beach was based on an 1884 survey map and on aerial photographs taken in the period from 1928 to 1975. The actual measurements on shoreline changes were obtained only from the aerial photographs, because the survey map was not sufficiently accurate to provide reliable measurements.

The method of using aerial photographs involves scaling each photograph and then measuring from a fixed-stable object to the water and vegetation lines (Hwang 1980). By comparing the measurements on photographs from different years, the changes at Waimea Beach could be determined. Possible tilt errors were minimized by scaling each photograph in a direction parallel to the shoreline measurement; possible relief displacement was minimized by working only in the center of the photograph and selecting stable objects with low relief. Finally, all measurements were made with a fine-precision ruler and a 10 × magnifying glass.

The maximum error for measurements made during this study is 9 ft. This number was obtained by determining the distance on all the photographs between the stable reference point and a basalt rock on the beach. The range in the measurements gives an approximation of the errors.

Although measurements were made to both the water and vegetation lines, we have used only the vegetation line because it is the more accurate indication of long-term change. Use of the water line would introduce problems concerning wave runup, light reflection, and tidal changes. Furthermore, the water line has a large seasonal change superimposed on the long-term trend, and it is not always possible to separate the two, even for photographs taken during the same time of year. Use of the vegetation line eliminates many of these problems. For beaches that have accreted over a long term, the vegetation tends to extend seaward. If the beach recedes, the vegetation becomes more susceptible to erosion by wave inundation and thus shows the shoreline retreat.

The 1884 survey map of Waimea Bay reveals that the water line was once seaward of Table Rock (Figure 4). A 1928 photograph also shows this rock surrounded by sand. Today, Table Rock is used as a diving platform; thus, it is apparent that Waimea Beach has receded considerably.

Figure 5 shows the historic changes in the position of the water and vegetation lines. Over a 47-yr period, the net landward movement of the water line was 195 ft. The largest loss occurred during the period 1928–1962, when 215 ft of erosion was recorded. It is not known how much of this change is seasonal as opposed to long-term. However, the 1962 photograph was taken at the end of summer, when the beach should have been in the state of maximum accretion. Therefore, the 215 ft of erosion may actually be an underestimate of the real long-term change. The water line retreat may have been due to a sand mining operation conducted at Waimea Bay, although the full impact of this industry on the beach is unknown.

From August 1962 to April 1967, the water line moved seaward about 75 ft. During the next observation period to January 1971, the beach receded about 60 ft.

The changes in the vegetation line show a different trend. From 1928 to 1949, the vegetation line receded 63 ft. Because of lack of aerial photographic coverage, it is not known whether this loss occurred at a steady 3 ft/yr or in one or more rapid pulses. Perhaps some of the erosion was caused by the 1946 tsunami, which did tremendous damage to the north shore of Oahu. From 1949 to 1967, the vegetation line receded at a rate of about 1–2 ft/yr. This loss was concurrent with major sand mining operations at Waimea Beach.

From 1967 to 1971, the vegetation line retreated 56 ft, or about 14 ft/yr, but this loss was not steady and much of it occurred during the large storm of 1–2 December 1969. During that storm, waves estimated at over 50 ft high filled Waimea Bay with turbulent water. Photographs show storm waves cutting a scarp in the beach face, the top of which marked the vegetation line. Inundation was more than 750 ft inland, and several sections of the highway and parking lot were covered with rock and sand. It appears that sand put into suspension by the turbulent water in the bay due to this storm was deposited outside the breaker zone at depths where summer waves cannot move sediment shoreward. Thus, the sand was permanently removed from the beach system.

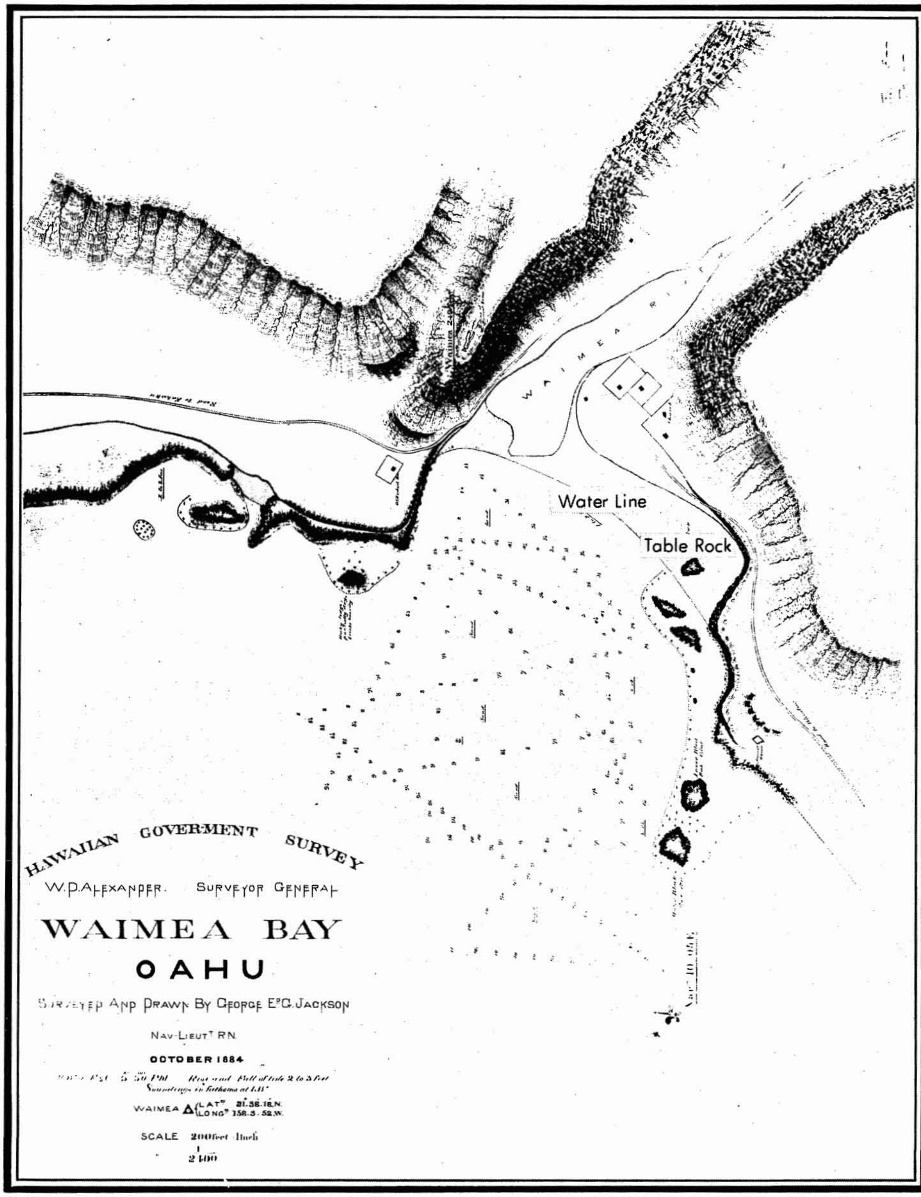

FIGURE 4. The 1884 survey map of Waimea Bay, Oahu, made by E. D. Jackson. Note the position of Table Rock landward of the indicated water line, compared with present location shown in Figure 1.

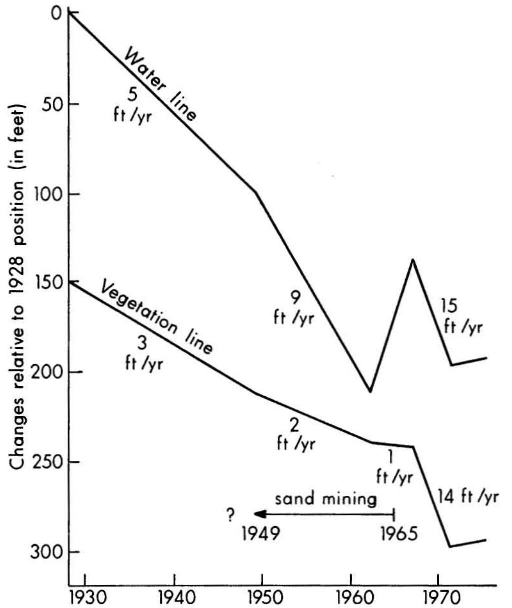

FIGURE 5. Changes in the water and vegetation lines relative to their position in 1928.

The highest rates of erosion for both the water and vegetation lines occurred from 1967 to 1971 (Figure 5). The rates of retreat were 14–15 ft/yr when averaged over this 4-yr period.

It is apparent that large winter storms are a major mechanism of shoreline retreat at Waimea Beach. The historic data for the vegetation line show long periods where slight erosion of 1–3 ft/yr alternate with storm events that cause massive change.

SOURCES OF SAND AND MODES OF SAND LOSS AT WAIMEA

The offshore morphology and its relationship to the Pleistocene sea level history are critical factors in the recent history of the beach in Waimea Bay. Stearns' (1978) latest chronology of Hawaiian sea level stands has the Makai Range stand (−60 ft) occurring during the last part of the last major glaciation. This is followed by a retreat of the sea to the Mamala level (−350 ft) and then a rise to its present level, with a brief stop at −15 ft and a possible short period at +5 ft. Figure 6 shows that during the −60-ft sea level stand the shoreline along this coast of Oahu was relatively straight, and it is likely that the beach that existed off Waimea Valley would have been in direct contact with beaches to either side of the valley and a part of a much larger littoral system. When sea level dropped to the Mamala level, there was a continuous beach along this shore (Figure 3), and large reservoirs of sand were likely exposed above sea level (Stearns 1978). As the sea again rose to its present level, the headlands surrounding Waimea Bay became barriers cutting off the beach in the bay from the larger littoral system. When this happened, the sources of sand to keep the beach nourished were restricted to those produced in the bay itself.

Moberly and Chamberlain (1964) found that the beach sand at Waimea is composed of 95–99 percent calcareous material. This composition shows that, at present, the sediment added to this beach by erosion of the basaltic headlands enclosing the bay and from sediment brought to the beach by occasional flooding of the Waimea stream is minor compared to the biogenic component. Because there are no large reefs producing new sand in Waimea Bay and the bay is cut off from littoral drift from the larger beaches to either side by the rocky headlands and deep offshore waters, much of the sand found in the bay must be relic sands produced during a lower stand of sea level. If this is so, then the measured loss of sand from Waimea Bay littoral system can be attributed to the lack of a supply of new sand as well as to processes that are removing the sand.

The primary avenues of sand loss at Waimea are probably abrasion, removal by humans, and deposition in deeper water outside the littoral system. Moberly (1968) showed that abrasion is a significant factor in the loss of sand in Hawaii; this mechanism is probably especially characteristic of beaches like Waimea that are subject to attack by large waves every winter. Since abrasion is caused by the impact of sand grains against each other, it seems reason-

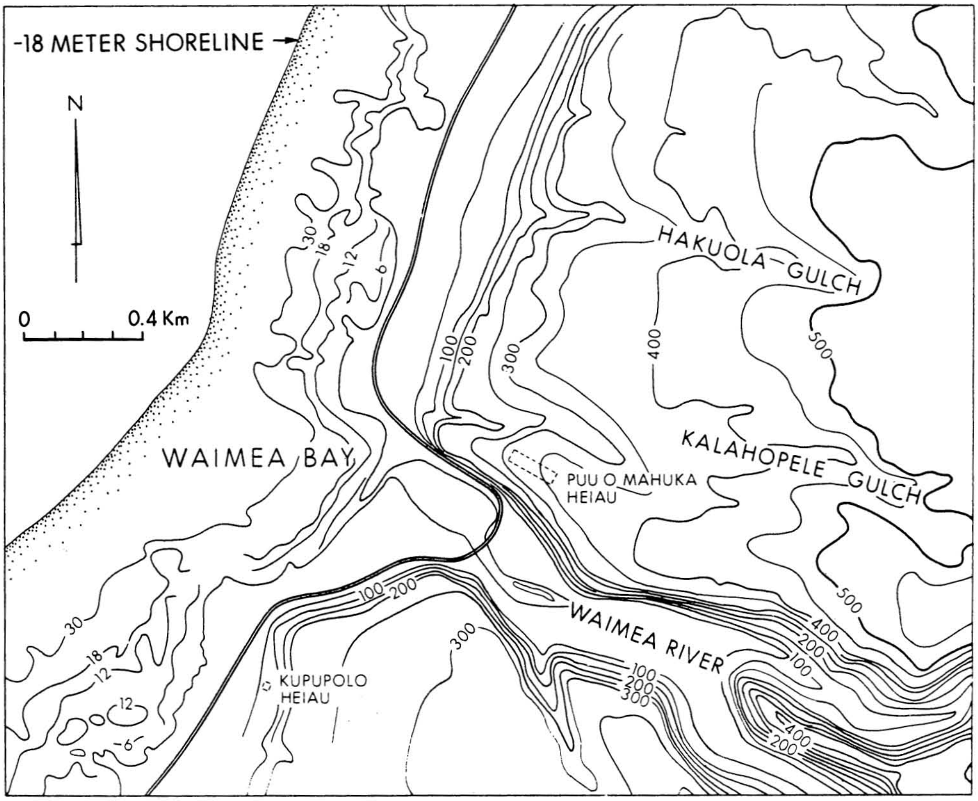

FIGURE 6. The location of the −18-m (−60-ft) shoreline shown on a map of the present topography and bathymetry of the Waimea Bay vicinity. Contours in feet above and below the present sea level.

able to assume that loss rates from abrasion should remain relatively constant. Our aerial photograph measurements indicate that the major episodes of erosion at Waimea Beach were intermittent; this suggests that the loss of sand by abrasion may be small compared to other avenues of loss.

Like many other beaches on Oahu, Waimea was mined to provide aggregate for concrete and road materials. The amount of sand removed from the beach at Waimea is unknown. We have evidence of mining between 1949 and 1957, but we can only estimate the possible volume of sand that was removed. We do not know whether the mining operation was continuous or only occasional; however, even a maximum value for the estimated volume of sand removed is still smaller than the total volume we calculated has been lost from the beach. The aerial photograph measurements show that the major erosion events at Waimea Beach occurred during the 1928–1949 and 1967–1971 intervals, periods during which little or no mining occurred. Thus, we believe that although mining may have caused some shoreline retreat, it was not the only factor.

Analysis of old maps and aerial photographs provides evidence of periods with very little change and other periods during which changes appear to be fairly large (Figure 4). The rapid erosion due to the December 1969 storm may be indicative of the major mode of erosion at Waimea Beach: occasional large storms or tsunamis and hurricanes that have the capability of moving sand into deeper waters where it may be permanently lost from the beach system.

CONCLUSIONS

Our major conclusion on erosion at Waimea Bay is that since being cut off from sand supplied by other sections of the coastline, the bay is not producing enough sand to replace that being lost. The major cause of the loss appears to be sand moved into deeper water by occasional events such as the December 1969 storm.

This conclusion allows us to predict that the beach in Waimea Bay will continue to erode at an unpredictable rate that is dependent primarily on the frequency of large storms, hurricanes, and tsunamis. Because of the unpredictable nature of these events, we recommend that aerial photographs of the bay be taken periodically and analyzed using the technique outlined in this paper to monitor the shoreline changes. This information can then be used as the basis for making decisions on possible danger to the public facilities that presently exist at Waimea and where to build new facilities in the future.

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